# Site Validation Based on the Use of Broadband Calculable Antennas and Numerical Simulations

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***Abstract*—Semi-anechoic chambers and open area test sites validation in the frequency range between 30 MHz and 1000 MHz is typically carried out by comparing measurement results obtained by using a pair of biconical and log-periodic (broadband) dipole antennas with tabulated reference values of normalized site attenuation (NSA) provided by CISPR and ANSI standards. It is here shown, through simulations based on validated electromagnetic models of biconical and log-periodic dipole antennas, that the NSA reference values reported in the CISPR 16-1-4 and ANSI C63.4 standards may differ up to about 3 dB from those obtained by using pairs of calculable broadband antennas. Large deviations are observed both in the lower frequency range (30 MHz – 250 MHz), where the use of the biconical antenna pair is prescribed, and in the higher frequency (300 MHz – 1 GHz), where a pair of log-periodic dipole antennas is required. The observed 3 dB deviation is not negligible since the tolerance set by the standard is ± 4 dB.**

***Index Terms*—antennas, electormagnetidcs, propagation, measurements.**

## I. INTRODUCTION

Adequate performance of semi-anechoic chambers (SAC) and open area test sites (OATS) is verified by comparing the attenuation between a pair of broadband antennas (the so called site attenuation, SA, expressed in dB) normalized by sum of the antenna factors (each expressed in dB($m^{-1}$)) of the two antennas with tabulated reference values of normalized site attenuation (NSA, in dB($m^2$)) [1, 2]. The tolerance on the deviation between measured and tabulated values is ± 4 dB over the full frequency range from 30 MHz to 1000 MHz.

The tabulated NSA reference values from 30 MHz to 1000 MHz are calculated assuming that an ideal pair of short dipoles having a $\sin\theta$ pattern over the E-plane and isotropic over the H-plane are used as transmitting and receiving antennas. Near field effects, coupling between the dipoles and between the dipoles and their images are neglected. The resulting NSA values in linear units are therefore calculated through the following formulas (horizontal polarization)

$$NSA_H = \frac{1}{k_H} \cdot \lambda d \cdot \frac{R}{\zeta}, \tag{1}$$

where

$$k_H = d \left| \frac{e^{-j2\pi\frac{r}{\lambda}}}{r} - \frac{e^{-j2\pi\frac{r'}{\lambda}}}{r'} \right|_{\mathrm{MAX}}, \tag{2}$$

and (vertical polarization)

$$NSA_V = \frac{1}{k_V} \cdot \lambda d \cdot \frac{R}{\zeta}, \tag{3}$$

where

$$k_V = d \left| \frac{e^{-j2\pi\frac{r}{\lambda}}}{r} \left(\frac{d}{r}\right)^2 + \frac{e^{-j2\pi\frac{r'}{\lambda}}}{r'} \left(\frac{d}{r'}\right)^2 \right|_{\mathrm{MAX}}. \tag{4}$$

$d$ represents the horizontal distance between the transmitting and receiving antenna, $h_T$ is the height of the transmitting antenna, $h_R$ is the height of the receiving antenna, $r = \sqrt{d^2 + (h_R - h_T)^2}$ is the distance between the transmitting antenna and receiving antenna, $r' = \sqrt{d^2 + (h_R + h_T)^2}$ is the distance between the image of the transmitting antenna and the receiving antenna, $\lambda$ is the wavelength, the maximum is taken over the range of height scanned by the receiving antenna and the metallic plane is a flat, infinite size, perfect conductor. Values of NSA for the following standard geometry are reported in Table 1: distance $d = 3$ m, transmit antenna height $h_T$ of 1 m and 2 m (horizontal polarization) or 1 m and 1.5 m (vertical polarization) and receive antenna height $h_R$ scanning from 1 m to 4 m.

It is known, see [3] and [4], that NSA values calculated through (1) to (4) in the frequency range from 30 MHz to 200 MHz may deviate by more than 2 dB from those numerically calculated accounting for near field and mutual coupling effects and assuming that a standard pair of biconical antennas is used to transmit and receive. Geometry Specific Correction Factors (GSCFs) are indeed introduced by ANSI in the standard [3] in order to better fit to reality in this frequency range. Very recently the same approach has been proposed by CISPR to national committees through a document for comment [5].

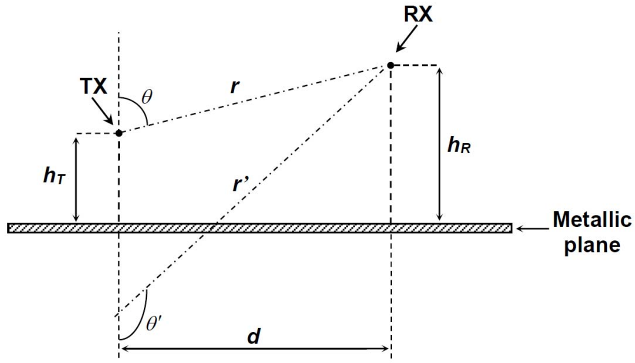


Fig. 1. Geometrical configuration of NSA verification.

CISPR provides a correction similar (but not identical) to the GSCF and in the same frequency range from 30 MHz to 200 MHz. ANSI and CISPR correction factors are calculated through electromagnetic simulations carried out by using the Numerical Electromagnetic Code (NEC). The maximum absolute value of the ANSI correction is 2.4 dB and the maximum absolute value of the CISPR correction is 2.6 dB, both in the case of vertical polarization, $h_T$ = 1.5 m and $f$ = 200 MHz.

Table 1. Values of NSA calculated through (1) to (4).

| $f$ (MHz) | $NSA_H$ $h_T$ = 1 m (dBm$^2$) | $NSA_H$ $h_T$ = 2 m (dBm$^2$) | $NSA_V$ $h_T$ = 1 m (dBm$^2$) | $NSA_V$ $h_T$ = 1.5 m (dBm$^2$) |
|---|---|---|---|---|
| 30 | 15.8 | 11.0 | 8.2 | 9.3 |
| 35 | 13.4 | 8.8 | 6.9 | 8.0 |
| 40 | 11.3 | 7.0 | 5.8 | 7.0 |
| 45 | 9.4 | 5.5 | 4.9 | 6.1 |
| 50 | 7.8 | 4.2 | 4.0 | 5.3 |
| 60 | 5.0 | 2.2 | 2.6 | 4.1 |
| 70 | 2.8 | 0.6 | 1.5 | 3.2 |
| 80 | 0.9 | -0.7 | 0.6 | 2.6 |
| 90 | -0.7 | -1.8 | -0.1 | 2.1 |
| 100 | -2.1 | -2.8 | -0.7 | 1.9 |
| 120 | -4.2 | -4.4 | -1.5 | 1.2 |
| 140 | -6.0 | -5.8 | -1.8 | -1.5 |
| 160 | -7.4 | -6.7 | -1.7 | -3.7 |
| 180 | -8.6 | -7.2 | -1.3 | -5.3 |
| 200 | -9.6 | -8.4 | -3.6 | -6.7 |
| 250 | -11.7 | -10.6 | -7.7 | -9.1 |
| 300 | -12.8 | -12.3 | -10.5 | -10.9 |
| 400 | -14.8 | -14.9 | -14.0 | -12.6 |
| 500 | -17.3 | -16.7 | -16.4 | -15.1 |
| 600 | -19.1 | -18.3 | -16.3 | -16.9 |
| 700 | -20.6 | -19.7 | -18.4 | -18.4 |
| 800 | -21.3 | -20.8 | -20.0 | -19.3 |
| 900 | -22.5 | -21.8 | -21.3 | -20.4 |
| 1000 | -23.5 | -22.7 | -22.4 | -21.4 |

The corrected values of NSA are reported in Table 2 (ANSI) and Table 3 (CISPR). The maximum absolute difference between the ANSI and CISPR corrected values is 0.8 dB (compare Table 3 and Table 4, $NSA_V$, $h_T$ = 1 m, $f$ = 60 MHz). The dimensions of the simulated biconical antennas are quite similar between ANSI and CISPR being both based on the original MIL STD 461A design.

Table 2. Corrected values of NSA – ANSI, 50 Ω balun.

| $f$ (MHz) | $NSA_H$ $h_T$ = 1 m (dBm$^2$) | $NSA_H$ $h_T$ = 2 m (dBm$^2$) | $NSA_V$ $h_T$ = 1 m (dBm$^2$) | $NSA_V$ $h_T$ = 1.5 m (dBm$^2$) |
|---|---|---|---|---|
| 30 | 17.8 | 12.7 | 8.0 | 9.0 |
| 35 | 14.8 | 10.0 | 6.4 | 7.6 |
| 40 | 12.3 | 8.0 | 5.2 | 6.5 |
| 45 | 10.1 | 6.4 | 4.4 | 5.7 |
| 50 | 8.0 | 5.2 | 3.9 | 5.2 |
| 60 | 4.5 | 3.4 | 4.0 | 4.9 |
| 70 | 2.8 | 0.5 | 3.3 | 3.8 |
| 80 | 1.8 | -1.4 | 1.9 | 2.6 |
| 90 | 0.5 | -2.4 | 0.2 | 1.6 |
| 100 | -1.1 | -3.2 | -1.1 | 1.0 |
| 120 | -3.8 | -4.2 | -2.2 | 0.9 |
| 140 | -5.9 | -5.9 | -2.5 | 0.3 |
| 160 | -7.4 | -7.2 | -2.5 | -1.7 |
| 180 | -8.3 | -7.1 | -2.5 | -3.1 |
| 200 | -9.0 | -7.6 | -2.8 | -4.3 |

Corrected values of NSA are provided for 3 m and 10 m distances and 50 Ω and 200 Ω impedance baluns by ANSI and 3 m, 5 m and 10 m distance and 50 Ω and 200 Ω impedance baluns by CISPR. We here restrict the analysis to the 3 m distance because it is by far the most common distance adopted by testing laboratories and the one to which the largest corrections apply. Further, the 50 Ω balun is here considered (see section II.A.).

Table 3. Corrected values of NSA – CISPR, 50 Ω balun.

| $f$ (MHz) | $NSA_H$ $h_T$ = 1 m (dBm$^2$) | $NSA_H$ $h_T$ = 2 m (dBm$^2$) | $NSA_V$ $h_T$ = 1 m (dBm$^2$) | $NSA_V$ $h_T$ = 1.5 m (dBm$^2$) |
|---|---|---|---|---|
| 30 | 17.8 | 12.7 | 7.8 | 8.9 |
| 35 | 14.8 | 10.0 | 6.2 | 7.4 |
| 40 | 12.2 | 8.0 | 5.0 | 6.3 |
| 45 | 9.9 | 6.4 | 4.2 | 5.7 |
| 50 | 7.7 | 5.4 | 4.1 | 5.4 |
| 60 | 4.4 | 3.3 | 4.7 | 5.3 |
| 70 | 3.1 | 0.1 | 3.6 | 3.7 |
| 80 | 2.0 | -1.5 | 1.8 | 2.5 |
| 90 | 0.5 | -2.4 | 0.1 | 1.5 |
| 100 | -1.1 | -3.2 | -1.1 | 1.0 |
| 120 | -3.8 | -4.2 | -2.2 | 0.8 |
| 140 | -5.9 | -5.9 | -2.5 | 0.5 |
| 160 | -7.4 | -7.2 | -2.5 | -1.4 |
| 180 | -8.3 | -7.0 | -2.7 | -2.9 |
| 200 | -8.9 | -7.5 | -3.0 | -4.0 |

It is important to highlight that no correction is provided neither by ANSI nor by CISPR above 200 MHz and up to 1 GHz, i.e. in the frequency range where the use of a pair of log-periodic dipole array (LPDA) antennas is recommended. One of the scopes of this contribution is to fill the gap deriving corrected NSA reference values for LPDA antennas. It is shown that the correction is systematic (a larger NSA is predicted with respect to that reported in Table 1), it tends to increase with frequency, and it is quite significant (up to 3.2 dB at 1000 MHz). Another scope of this contribution is to quantify how well the numerical model simulates real (commercial) biconical and LPDA antennas having standard dimensions. This is an important aspect to consider in order to give credibility to the simulations and to quantify the uncertainties involved in the NSA verification, as stressed also in [6]. The commercial broadband antennas here considered are calculable within an uncertainty comparable with their calibration uncertainty.

This paper is structured as follows. In the next section II, the results supporting the validity of the numerical models of the biconical and LPDA calculable antennas are presented. In section III, the results of the NSA simulation based on the previously validated numerical models are derived and discussed. Conclusive remarks are reported in section IV.

## II. Calculable Biconical and LPDA Antennas

We here provide evidence of validity of the numerical models of a commercial biconical and LPDA antennas. Both models are produced by the same manufacturer (Schwarzbeck Mess - Elektronik OHG) and are owned by the institution of the first author. These antennas have been extensively used as reference antennas for calibration of travelling samples for interlaboratory comparisons of radiated emission measurements coordinated by the authors and documented by several publications [7-16]. The simulation software here adopted is FEKO [17], a well-known commercial tool based on method of moments.

### A. Biconical antenna

The simulated biconical antenna is the combination of the BBA 9106 biconical radiating elements with the 50 Ω (1:1) balun VHA 9103 [18]. The 200 Ω (4:1) balun VHBB 9124 is also available for combination with the same BBA 9106 radiating elements but the analysis will be limited here to the 50 Ω balun for sake of brevity. The computer aided design (CAD) model of the biconical antenna is shown in Fig. 2.

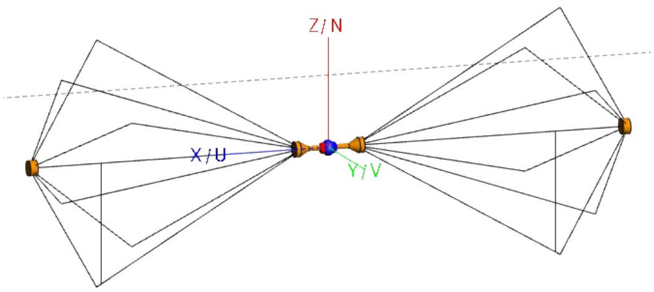


Fig. 2. CAD model of the biconical antenna.

The overall length of the biconical antenna is 131 cm and the cone diameter is 53 cm. The meshing of the structure consists of 622 segments and 418 triangles. The average edge length is 12.9 mm and the standard deviation is 4.5 mm. The numerically calculated antenna factor (AF) and the AF provided by the manufacturer through calibration are compared in Table 4. The simulation reproduces the calibration carried out by the manufacturer in order to determine the free space AF. Two identical antennas are placed in front of each other at 4 m distance and the insertion loss between the two antennas is measured. The gain of the two antennas (and AF from the gain) is obtained from the Friis formula. The reference point for distance measurement between the biconical antennas is their phase center. Free space is easily reproduced in the simulated environment. The manufacturer determines free-space AF through measurements above a large conducting ground plane and averaging the insertion loss over a height scan of both transmitting and receiving antennas [19]. Evidence of the capability to calibrate AF within the stated expanded uncertainty was provided by the manufacturer through participation in a European intercomparison in the frequency range from 30 MHz to 1 GHz [19]. The maximum deviation between the calculated and calibrated AFs is 0.9 dB, comparable with the expanded uncertainty of calibration of 0.7 dB. This comparison validates the numerical model of the biconical antenna.

Table 4. AF calculated by using FEKO and AF provided by the manufacturer of the biconical antenna.

| *f* (MHz) | AF FEKO (dB/m) | AF SCHWARZBECK (dB/m) | Deviation (dB) |
|---|---|---|---|
| 30 | 19.2 | 19.5 | -0.3 |
| 35 | 17.2 | 17.0 | 0.2 |
| 40 | 15.3 | 15.1 | 0.2 |
| 45 | 13.4 | 12.8 | 0.6 |
| 50 | 11.5 | 11.0 | 0.5 |
| 60 | 7.9 | 8.4 | -0.5 |
| 70 | 6.0 | 6.1 | -0.1 |
| 80 | 6.7 | 6.9 | -0.2 |
| 90 | 8.6 | 8.9 | -0.3 |
| 100 | 10.4 | 10.4 | 0.0 |
| 110 | 11.9 | 11.8 | 0.1 |
| 120 | 13.0 | 12.9 | 0.1 |
| 130 | 14.0 | 13.8 | 0.2 |
| 140 | 14.7 | 14.4 | 0.3 |
| 150 | 15.4 | 14.8 | 0.6 |
| 160 | 15.9 | 15.4 | 0.5 |
| 170 | 16.3 | 15.8 | 0.5 |
| 180 | 16.7 | 16.1 | 0.6 |
| 190 | 17.0 | 16.4 | 0.6 |
| 200 | 17.2 | 16.5 | 0.7 |
| 210 | 17.5 | 16.6 | 0.9 |
| 220 | 17.7 | 16.9 | 0.8 |
| 230 | 17.8 | 17.2 | 0.6 |
| 240 | 18.0 | 17.5 | 0.5 |
| 250 | 18.2 | 17.5 | 0.7 |
| 260 | 18.4 | 17.8 | 0.6 |
| 270 | 18.7 | 18.3 | 0.4 |
| 280 | 19.1 | 18.7 | 0.4 |
| 290 | 19.6 | 19.1 | 0.5 |
| 300 | 20.4 | 20.3 | 0.1 |

### B. LPDA Antenna

The model of the simulated LPDA antenna is VUSLP 9111B. The size of the antenna is represented by the distance between the tip and the pair of elements of maximum length, which is 60 cm, and the overall length of these elements, which is 77.6 cm. The simulated structure is discretized through 3633 triangles whose average edge length is 12.1 mm and the standard deviation is 8.0 mm. The CAD model of the LPDA antenna is shown in Fig. 3. The simulation reproduces the calibration of the manufacturer, which consists in the measurement of the insertion loss between the terminals of a pair of identical LPDA antennas placed in front of each other at 3 m distance (gain is then obtained through the Friis formula, and AF is obtained from gain).

Fig. 3. CAD model of the LPDA antenna.

The reference point of the LPDA antenna for distance measurement is halfway between the tip and the pair of elements of maximum length. Free space AF is determined both through simulation and measurement. The comparison between the simulated and calibrated AF is reported in Table 5. The maximum deviation between the two AFs is 0.6 dB which is less than the expanded uncertainty of calibration (0.7 dB). This comparison validates the numerical model of the LPDA antenna.

Table 5. AF calculated by using FEKO and AF provided by the manufacturer of the LPDA antenna.

| ***f*** **(MHz)** | **AF FEKO (dB/m)** | **AF SCHWARZBECK (dB/m)** | **Deviation (dB)** |
|---|---|---|---|
| 300 | 13.2 | 13.8 | -0.6 |
| 350 | 15.0 | 14.8 | 0.2 |
| 400 | 15.4 | 15.5 | -0.1 |
| 450 | 16.0 | 16.2 | -0.2 |
| 500 | 16.7 | 17.1 | -0.4 |
| 550 | 16.9 | 17.5 | -0.6 |
| 600 | 18.0 | 18.5 | -0.5 |
| 650 | 18.8 | 18.8 | 0.1 |
| 700 | 19.4 | 19.2 | 0.2 |
| 750 | 19.5 | 19.8 | -0.3 |
| 800 | 19.9 | 20.2 | -0.3 |
| 850 | 20.4 | 21.0 | -0.5 |
| 900 | 21.3 | 21.3 | 0.0 |
| 950 | 21.1 | 21.5 | -0.3 |
| 1000 | 21.7 | 22.0 | -0.3 |

## III. NSA Values Obtained Through the Calculable Biconical and LPDA Antennas

The simulated NSA values are obtained by mimicking the corresponding NSA measurement procedure. The values in the frequency range from 30 MHz to 250 MHz are calculated by using the numerical model of the biconical antenna. Those from 300 MHz to 1 GHz are calculated by using the numerical model of the LPDA antenna. The height scan of the receiving antenna, from 1 m to 4 m, has been discretized through 10 cm steps (31 steps). A spot verification has been done at 1000 MHz with a finer step of 5 cm (61 steps) in order to check if the 10 cm step is too coarse to detect the minimum of the SA with adequate accuracy. The result of this verification is a maximum deviation of 0.054 dB between the minimum SA obtained with 10 cm and 5 cm steps. Then the 10 cm step is adequate.

Table 6. Values of NSA calculated by using the numerical models of the biconical and LPDA antennas.

| ***f*** **(MHz)** | $NSA_H$ $h_T = 1$ m ($dBm^2$) | $NSA_H$ $h_T = 2$ m ($dBm^2$) | $NSA_V$ $h_T = 1$ m ($dBm^2$) | $NSA_V$ $h_T = 1.5$ m ($dBm^2$) |
|---|---|---|---|---|
| 30 | 17.5 | 12.4 | 8.1 | 9.1 |
| 35 | 14.7 | 10.0 | 6.7 | 7.8 |
| 40 | 12.3 | 8.0 | 5.6 | 6.8 |
| 45 | 10.2 | 6.4 | 4.7 | 6.0 |
| 50 | 8.2 | 5.2 | 4.1 | 5.5 |
| 60 | 4.5 | 3.5 | 3.8 | 5.0 |
| 70 | 2.1 | 0.7 | 3.3 | 3.9 |
| 80 | 1.4 | -1.8 | 2.1 | 2.5 |
| 90 | 0.6 | -2.6 | 0.4 | 1.5 |
| 100 | -1.0 | -3.4 | -1.2 | 0.8 |
| 120 | -3.9 | -4.2 | -2.2 | 0.9 |
| 140 | -6.1 | -6.1 | -2.6 | 0.3 |
| 160 | -7.7 | -7.5 | -2.6 | -1.8 |
| 180 | -8.7 | -7.3 | -2.7 | -3.4 |
| 200 | -9.2 | -8.0 | -3.0 | -4.8 |
| 250 | -10.3 | -10.5 | -4.1 | -7.2 |
| 300 | -12.4 | -11.1 | -9.1 | -9.9 |
| 400 | -13.4 | -13.3 | -12.9 | -11.4 |
| 500 | -15.7 | -14.5 | -14.6 | -13.7 |
| 600 | -17.8 | -16.1 | -14.0 | -14.6 |
| 700 | -18.8 | -17.2 | -16.8 | -16.6 |
| 800 | -19.4 | -18.2 | -17.8 | -17.2 |
| 900 | -20.8 | -19.6 | -18.9 | -18.6 |
| 1000 | -22.0 | -19.8 | -19.2 | -19.3 |

The deviation between the values in Table 6 and Table 2 in the common frequency range from 30 MHz to 200 MHz is comprised between –0.7 dB and 0.4 dB. Similarly, comparing Table 6 with Table 3 the deviation results to be within –1.0 dB and 0.6 dB. These figures quantify the residual deviation that could be expected between measurements and tabulated values once that CISPR and ANSI corrections are applied. Note also that the deviation between CISPR and ANSI corrections is comprised between –0.8 and 0.4 dB.

In the frequency range from 300 MHz and 1000 MHz Table 6 is compared with Table 1. No correction values are indeed recommended by ANSI or CISPR in this frequency range. The outcome of this comparison is that the NSA values in Table 6 are systematically larger than those in Table 1 and the deviation tends to increase with increasing frequency. The maximum deviation is 3.2 dB at 1000 MHz in vertical polarization at $h_T = 1$ m. This result can be easily explained by the larger directivity of the LPDA antenna compared with the directivity of the simple short dipole model. A larger SA indeed results since the transmitting and receiving LPDAs are not aligned at the same height when the minimum SA is detected in the height scan.

## IV. Conclusion

Commercial biconical and LPDA antennas are available that can be calculated to within state-of-art calibration uncertainties, i.e. abundantly less than 1 dB. The numerical models of these calculable antennas can be exploited to generate reference NSA values whose closeness of agreement with reality is expected to be comparable with the accuracy of the numerical models themselves. Correction factors proposed by ANSI and CISPR in the frequency range between 30 MHz and 200 MHz are effective in reducing the discrepancies between measured and tabulated NSA values. However also the frequency range above 200 MHz and up to 1000 MHz requires consideration since discrepancies of about 3 dB are predicted in this frequency interval if no correction is applied to the original NSA tabulated values based on the short dipole transmitting and receiving antenna model.

## References


[1] ANSI C63.4-2014, “American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz,” American National Standards Institute, New York, 2014.

[2] CISPR 16-1-4, Ed. 4.0. 2019, “Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements,” INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE, -geneva, 2019.

[3] ANSI C63.5-2017, “American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz),” American National Standards Institute, New York, 2017.

[4] Zhong Chen, “Understanding Geometry Specific Correction Factors in ANSI C63.5,” 2010 Asia-Pacific International Symposium on Electromagnetic Compatibility, April 12 - 16, 2010, Beijing, China, pp. 561-564.

[5] CIS/A/1303/DC, “Correction Factors of Broadband Antennas Used for NSA Site Validation and Associated Uncertainty,” INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE (CISPR) SUBCOMMITTEE A: RADIO INTERFERENCE MEASUREMENTS AND STATISTICAL METHODS, Geneva, 2019-08-30.

[6] Zhong Chen, “Understanding Site Validation Measurements Below 1 GHz in ANSI Standards,” 2019 IEEE Int. Symp. on EMC, New Orleans (LO), Jul. 22-36, 2019, pp. 56-60.

[7] Carlo F. M. Carobbi, Marco Cati, Carlo Panconi, “Generation and Measurement of a Reference Field for Round-Robin Comparison Purposes”, in Proc. IEEE International Symp. on EMC, Detroit, Aug. 18-22, 2008.

[8] C. F. M. Carobbi, A. Bonci, M. Cati, C. Panconi, M. Borsero and G. Vizio, “Validation of Far-Field Numerical Predictions Through Near-Field Measurements,” ICEAA-IEEE APWC- EMS 2013 Symposium, September 9-13, 2013, Torino, Italy, pp. 551-554.

[9] Carlo F. M. Carobbi, Alessio Bonci, Marco Cati, Carlo Panconi, Michele Borsero and Giuseppe Vizio, “Design, Preparation, Conduct and Result of a Proficiency Test of Radiated Emission Measurements”, IEEE Transactions on Electromagnetic Compatibility, vol. 56, no. 6, pp. 1251-1261, Dec. 2014.

[10] Carobbi, C.; Bonci, A.; Cati, M.; Panconi, C.; Borsero, M. and Vizio, G. “Experience on proficiency testing in Italy with emphasis on radiated emission measurements from 30 MHz to 1 GHz,” Electromagnetic Compatibility (EMC), 2015 IEEE International Symposium on, Year: 2015, Pages: 473 - 478, DOI: 10.1109/ISEMC.2015.7256208.

[11] Carlo F. M. Carobbi, Alessio Bonci, Marco Cati, Carlo Panconi, Michele Borsero and Giuseppe Vizio, “Proficiency Testing by Using Traveling Samples With Preassigned Reference Values”, IEEE Transactions on Electromagnetic Compatibility, vol. 58, no. 4, pp. 1339 – 1348, Aug. 2016.

[12] Alessio Bonci, Enrico Boni, and Carlo F. M. Carobbi, “A Compact, Broadband, Calculable Electromagnetic Field Source for Quality Assurance in EMC Testing,” IEEE Transactions on Electromagnetic Compatibility, vol. 60, no. 5, pp. 1215 – 1222, Oct. 2018.

[13] Carlo Carobbi and Andrea Guadagnoli, “Low-Uncertainty Characterization of a Predictable Active and Broadband Antenna,” 13th European Conference on Antenna and Propagation (EuCAP), Krakow, Poland, March 31 – April 5, 2019.

[14] Carlo F. M. Carobbi, “On the Quantification of the Uncertainty of an Electromagnetic Prediction – An Application with Experimental Verification,” 2019 URSI Asia Pacific Radio Science Conference (AP-RASC), India Habitat Centre, New Delhi, Indi, 09 – 15 March, 2019.

[15] Carlo Carobbi and Andrea Guadagnoli, “The Combined use of Measurements and Simulations for the Low-Uncertainty Characterization of a Reference Source of Electromagnetic Field,” 2019 IEEE International Symposium on Measurements and Networking (M&N), Catania, 8-10 July 2019.

[16] Carlo Carobbi and Andrea Guadagnoli, “Measurements and Simulations of the Near-Field Generated by a Reference Source of Electromagnetic Field,” 2019 IEEE International Conference on RFID – Technology and Applications, Pisa (Italy), Sep. 25-27, 2019.

[17] Altair Feko™, https://altairhyperworks.com/product/FEKO. Web link as checked on Oct. 18, 2019.

[18] Schwarzbeck Mess-Elektronik OHG, http://www.schwarzbeck.de/en/. Web link as checked on Oct. 18, 2019.

[19] M. J. Alexander, “European Intercomparison of Antenna Factors in the Frequency Range 30 MHz to 1 GHz,” in IEE Proc. of Sci. Meas. and Tech., vol. 143, no. 4, pp. 229-240, Jul. 1996.